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The "Most Probable" Dust Blend and Its Response in the F-100 Hot Section Test System (HSTS)

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Technical Report

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The "most probable" dust blend, as well as dust mixtures used in previous combustor sections, were passed through a F-100 gas turbine engine hot-section test system. Some of the parameters controlling the deposition behavior were determined. A detailed description of the experimental results is included.

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PREFACE

This study was performed by the Calspan Corporation, Advanced Technology Center under support provided by the Defense Nuclear Agency, Contract No. DNA 001-89-C-0060. The authors gratefully acknowledge the contribution made to the success of this program by the DNA technical monitor, Major Douglas P. Wade, and to Dr. Edward L. Trimba, also of DNA. Thanks are also extended to the Calspan support staff, especially Jeffery Barton and Robert Field, who made valuable contributions to the success of this work. Last, we would like to acknowledge the helpful discussions provided by Pratt and Whitney during the design phase of the hot-section test system (HSTS).

CONVERSION TABLE

Conversion factors for U.S. customary to metric (SI) units of measurement

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E –10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter^2 (m^2)	1.000 000 X E –28
British Thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2(MJ/m^2)	4.184 000 X E –2
curie	giga becquerel (GBq)*	3.700 000 X E +1
degree (angle)	radian (rad)	1.745 329 X E –2
degree Fahrenheit	degree kelvin (K)	$T_K=(t^\circ f + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E –19
erg	joule (J)	1.000 000 X E –7
erg/second	watt (W)	1.000 000 X E –7
foot	meter (m)	3.048 000 X E –1
foot–pound–force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E –3
inch	meter (m)	2.540 000 X E –2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)	Gray (Gy)**	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E +3
ktap	newton–second/m^2 (N–s/m^2)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E –6
mil	meter (m)	2.540 000 X E –5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E –2
pound–force (lbf avoirdupois)	newton (N)	4.448 222
pound–force inch	newton–meter (N·m)	1.129 848 X E –1
pound–force/inch	newton/meter (N/m)	1.751 268 X E +2
pound–force/foot^2	kilo pascal (kPa)	4.788 026 X E –2
pound–force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound–mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E –1
pound–mass–foot^2 (moment of inertia)	kilogram–meter^2 (kg·m^2)	4.214 011 X E –2
pound–mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E +1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E –2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E –4
shake	second (s)	1.000 000 X E –8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0°C)	kilo pascal (kPa)	1.333 22 X E –1

*The becquerel (Bq) is the SI unit of radioactivity; Bq = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

This report describes the results of a series of tests designed to determine the behavior of a "most probable" dust blend in a F-100 engine combustor. This "most probable" dust blend is the best state-of-the-art prediction of materials produced during a typical laydown in the vicinity bounded by 54°-56° N latitude and 35°-40° E longitude. The soil types in this region are mainly sod-podzolic and grey forest. The portion of ground soil that was of most interest was the top 10 cm. The specific ingredients that were blended to build the "most probable" dust cloud were: 1) red art clay, 2) minspar 200 feldspar, 3) Ottawa quartz, 4) peat moss, and 5) a glass made from constituents 1-4 using ceramic forming and firing methods. An analysis of each of the above components is described in Dunn and Kim (1991).

This blend was tested previously in the T56 HSTS (Dunn and Kim--1991). In that work, none of the blends constructed using the new dust blend materials resulted in deposits on the vanes for the maximum temperatures achievable in the T56 combustor (~2150 °F). Measurements were repeated using two dust materials that were found to deposit in previous tests, blend 2 (containing black scoria) and Mt. St. Helens ash (MSH), with deposition being observed in both cases. These experiments with blend 2 and MSH verified that the T56 HSTS was operating properly, but the components of the "most probable" blend were not depositing. Black scoria was determined to be the component of blend 2 responsible for deposition. Furnace tests performed using the components of the "most probable" dust blend and blend 2 suggested that the initial water content of a material may not have a significant impact on whether or not a material will deposit. These results will be discussed in more detail later in this report.

The purpose of the test series reported here was to determine whether or not deposition of the "most probable" dust blend would occur at the higher turbine inlet temperatures (TIT) encountered in the F-100 engine, and to determine some of the parameters that control deposition. This information was needed in preparation for an upcoming test series that will utilize of a F-100 turbofan engine that is to be subjected to blends made up of the "most probable" blend constituents. Specifically, some of the parameters thought to control deposition are: 1) the amount of free-water in the dust blend, 2) the amount of bound water in the dust blend, 3) the amount of glass in the dust blend, 4) the turbine inlet temperature, and 5) the vane metal temperature. A test matrix designed to test each of the above parameters was jointly constructed by DNA and Calspan using results from the T56 HSTS, designated dust concentrations of interest, and turbine inlet temperatures from the nominal maximum for the T56 combustor (1394 K) to the nominal maximum for the F-100 combustor HSTS (1644 K). The order of priority for the test blends was determined assuming that it might be possible to complete a limited number of tests (which suggests that the most important tests should be run first). The test matrix is summarized on Fig. 1. Blend 7 is the "most probable" dust blend agreed to by DNA and it's consultants. Blends 5 and 8, which contain different amounts of peat moss, were designed to investigate the effect of free-water on deposition. A mixture with increased glass content, blend 9, was used to investigate the effect of glass concentration on deposition. Blend 10, a mixture with no glass but high free moisture was used to determine whether or not any minerals form significant deposits. Blend 10 completed the test matrix with the new glass material. Blend 2 was run to verify proper operation of the HSTS. Blend 2 was found to deposit in the two previous F-100 engine experiments, so deposition was expected to occur in the F-100 HSTS. Dried blend 2, a blend with the same primary composition as blend 2 but with the scoria component heated in an oven to drive off the trapped moisture, was used to determine the effect of bound water on deposition. The presence of impurities, e.g. water, in a mineral has the effect of lowering the melting temperature. If the bound water is driven off by heating, the melting temperature of the scoria should increase. If this is the case, then one would not expect to observe deposition when using the dried blend 2.

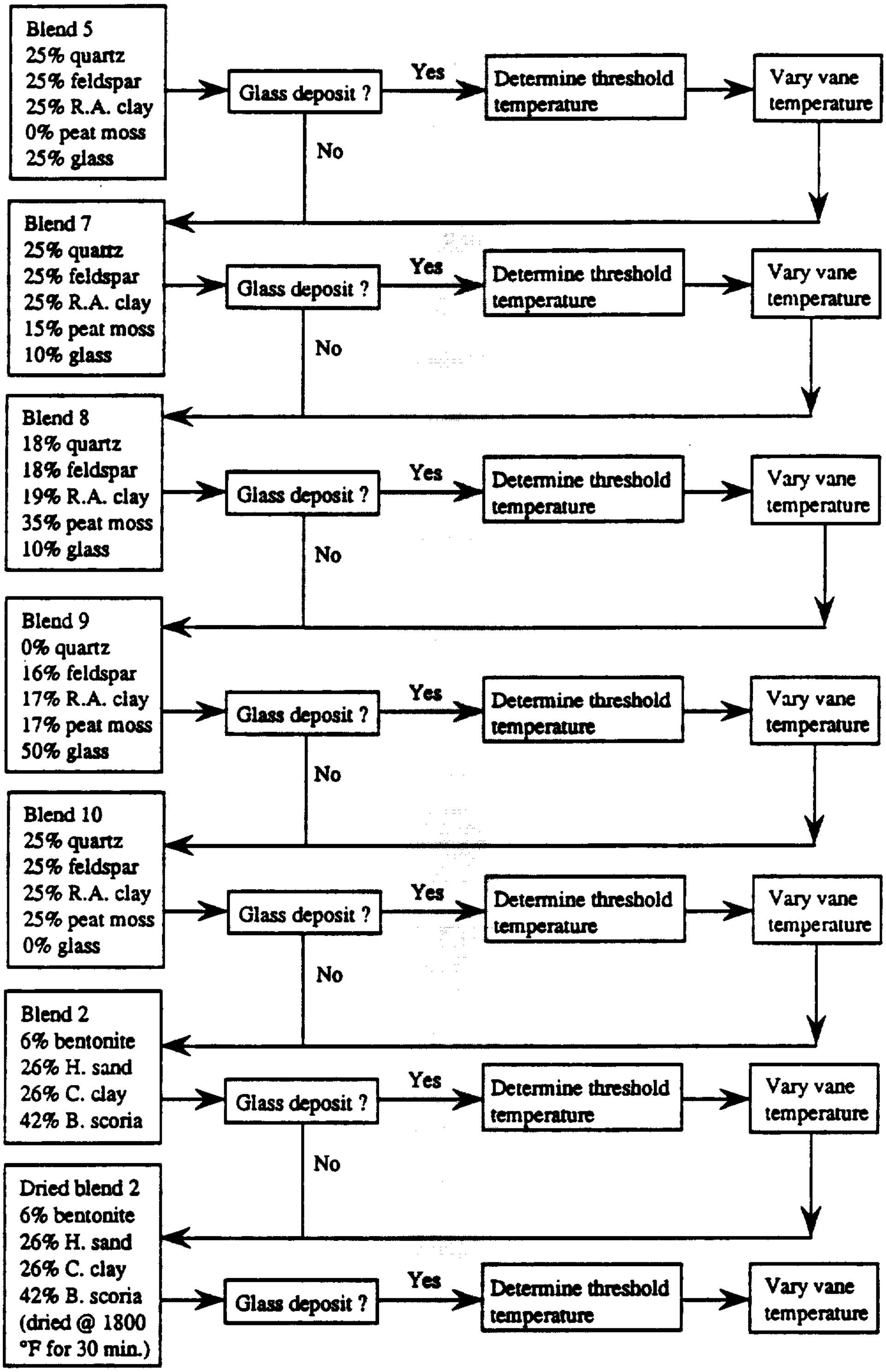


Fig. 1--Test matrix for F-100 combustor measurement program.

SECTION 2

EXPERIMENTAL TECHNIQUE AND TEST APPARATUS

2.1 TESTING OF ENGINE COMBUSTORS.

A decision was made early in this program to use actual engine hardware for the test in order to best simulate conditions encountered during engine operation in dust clouds. The combustor and associated hardware and high pressure turbine vanes from a F-100 engine were to build a test system. This test system, which is to be fed by an external pressure source (not the engine compressor), will be referred to hereafter as the HSTS. Shown on Table 1 are the operating parameters for the F-100 engine.

Table 1. Operating parameters for the F-100 engine.

	Sea level takeoff	25,000 ft cruise, M=0.7
w (kg/s)	53.6	28.1
P_t (MPa)	2.183	1.06
T_t (K)	1658	1459
Fuel flow (lpm)	84.7	38.2
F/A ratio	0.0254	0.0218
ΔP fuel nozzle (MPa)	1.14	0.725

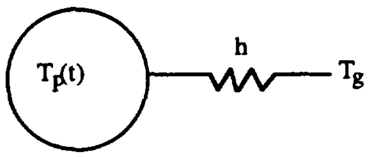
It is not necessary to operate the HSTS at these conditions, however. To duplicate the important flow parameters for the HSTS accurately, four conditions need to be satisfied: 1) The airflow distribution within the engine combustor must be duplicated. This can be performed by keeping the HSTS flow function (FF), given by

$$FF = \frac{\dot{w}\sqrt{T}}{P}$$

close to the value of FF in the engine. It can be seen that the ratio of airflow through the HSTS to that in the engine can be below unity as long as the pressure is reduced a corresponding amount. Discussions with Pratt and Whitney have indicated that the minimum test section pressure should be on the order of 0.55 MPa (80 psia) in order to avoid problems with atomization of fuel in the fuel nozzles. The implications are that the HSTS can be operated at about a third of the weight flow required for the engine. This represents a tremendous savings in air compressor rental costs along with a reduction in the associated noise level. The flow function can be computed to be $FF = 701 \frac{\frac{kg}{s}\sqrt{K}}{MPa}\left(14.3 \frac{\left(\frac{lb}{s}\right)\sqrt{°F}}{psia}\right)$ for the two engine operating conditions shown on Table 1. 2) For the purposes of this test program, it is desirable to keep the residence time of the particles within the combustor constant. If the flow function and temperature levels within the HSTS are matched, then this condition will be satisfied. The mass flow through the combustor is given by

$$\dot{w} = \rho Av = \frac{P}{RT} Av$$

If both the pressure and mass flow decrease by the same amount (to keep FF constant), the velocities within the HSTS and engine combustor (and therefore the particle residence times) will remain the same. 3) It is also desirable to keep the temperature within the HSTS close to the temperatures within the engine. This can be done by adjusting the fuel/air ratio. The HSTS external compressor delivers air at a temperature of ~356 K (180 °F), significantly lower than the engine compressor exit temperature of ~733 K (860 °F). The fuel/air ratio in the HSTS must therefore be increased in order to produce the correct exit temperatures. This can increase the combustor exit pattern factor, i.e., increase the non-uniformity in the combustor exit temperature, in addition to producing a smokey exhaust. These are, however, relatively minor problems. 4) Lastly, the thermal behavior of the particle in the HSTS should be similar to that in the engine. This is governed by the thermal time constant of the particle (τ_t), i.e., the time it takes for the initial particle to gas temperature difference to decay by a factor 1/e. For the configuration given below, the



thermal time constant can be calculated to be

$$\tau_t = \frac{m_p c_p}{hA} = f\left(\frac{d_p}{h}\right)$$

where the subscript p refers to the particle. It is necessary to keep τ_t for the HSTS equal to τ_t for the engine combustor. The Nusselt number for a sphere in cross-flow is given by

$$Nu = 0.37\left(\frac{v_\infty d_p \rho_f}{\mu_f}\right)^{0.6} = \frac{hd_p}{k_f}$$

where the subscript f refers to the fluid. Solving for h and substituting into the equation for τ_t yields

$$\tau_t = f\left(\frac{d_p^{1.4}}{\rho_f^{0.6}}\right)$$

where ρ_f is the fluid density. For particles 1 and 2,

$$\tau_t = f\left(\frac{d_{p,1}^{1.4}}{\rho_{f,1}^{0.6}}\right) = f\left(\frac{d_{p,2}^{1.4}}{\rho_{f,2}^{0.6}}\right)$$

or

$$\left(\frac{d_{p,1}}{d_{p,2}}\right) = \left(\frac{\rho_{f,1}}{\rho_{f,2}}\right)^{0.429} = \left(\left.\frac{P_{f,1}}{P_{f,2}}\right|_{T = \text{const}}\right)^{0.429}$$

The pressure ratio between the engine and the HSTS is ~3, resulting in an engine to HSTS particle diameter ratio of 1.48. The particle heat transfer will be duplicated if particles 1.48 times smaller than those originally intended are used. Since the particle sizes entering the combustor in the engine are not known to this level of accuracy, the differences in the heat transfer behavior of the particles entering the HSTS and the engine combustor may be neglected.

The benefits of using lower pressures and mass flows in the HSTS compared to the actual engine weight flow far outweigh the disadvantages. The lower pressure will be used for this test series.

The air mass flow rate in the test section must be maintained such that the flow function at the combustor inlet matches the FF in the engine. For a combustor entry pressure of 0.689 MPa (100 psia) and entry temperature of 356 K (180 °F), an air mass flow rate of 25.5 kg/s (56.3 lb/s) is required to match the flow function. For the HSTS used to perform the measurements reported here, the compressed air is supplied by external compressors (Atlas-Copco PTMS-1500). Each compressor is capable of supplying 42.4 m^3/min (1500 cfm) of air. Experience has indicated that is reasonable to plumb six of these compressors into the rig and that this number will supply the required pressure and weight flow of air. More compressors could be used if necessary. For atmospheric conditions of 294 K (70 °F) and 0.101 MPa (14.7 psia), a bank of six compressors provide a maximum mass flow rate of 5.08 kg/s (11.2 lb/s). This air flow is much lower than the 25.5 kg/s (56.3 lb/s) required to run the full combustor. However, to run a bank of thirty compressors would be unmanagable and also expensive. Therefore, a compromised position must be attained that allows a representative experiment to be performed at a reasonable cost and degree of complexity. This position was achieved by electing to operate one-quarter of the combustor as described below.

A F-100 engine combustor has 16 fuel nozzles equally spaced circumferentially. For the case where a quarter of the combustor (4 nozzles) is tested at a mass flow rate of 5.08 kg/s (11.2 lb/s) (six compressors) and a combustor entry temperature of 356 K (180 °F), a combustor entry pressure of 0.551 MPa (80 psia) is needed to match the engine combustor flow function. Discussions with Pratt and Whitney have indicated that this is a reasonable pressure at which to operate if problems with atomization of the fuel in the fuel nozzles are to be avoided.

The engine companies routinely test sectors of combustors, so the present test configuration is consistent with industry practice. Referring to Fig. 2, measurements are

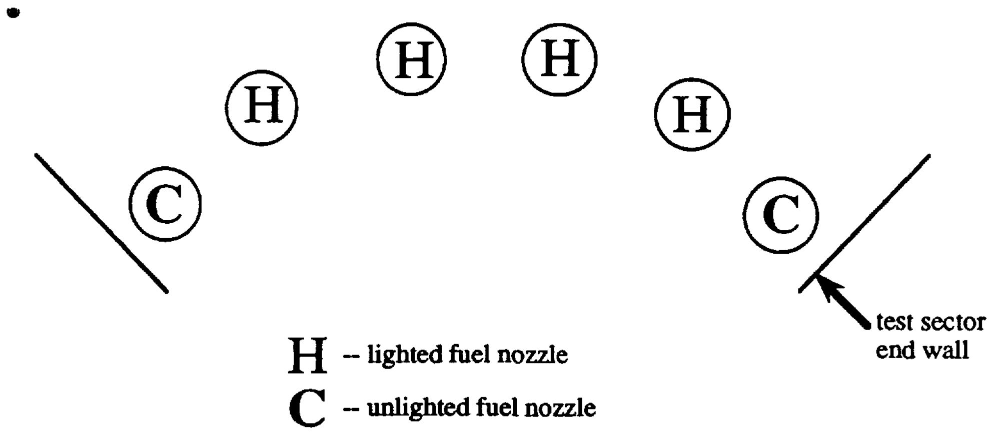


Figure 2. Schematic of combustor sector.

taken around the center two fuel nozzles. The two lighted fuel nozzles adjacent to them are used to obtain the proper boundary conditions. The two unlighted fuel nozzles at the ends are provided so that the airflow through them protects the test sector end walls from the hot combustion gases. The end fuel nozzles can be eliminated if the test sector end walls are made of a material (e.g.--a high temperature ceramic) that can withstand the high temperatures developed within the combustor. The decision was made to use such a ceramic material and in this way decrease the required airflow through the combustor by an additional 1/3.

2.2 DESCRIPTION OF F-100 HSTS.

A schematic of the test facility is shown on Fig. 3. A much more detailed description of the facility is given in Kim, Baran and Dunn (1991). The air enters a high pressure (0.965 MPa) chamber where it is metered. The mass flow rate through the test

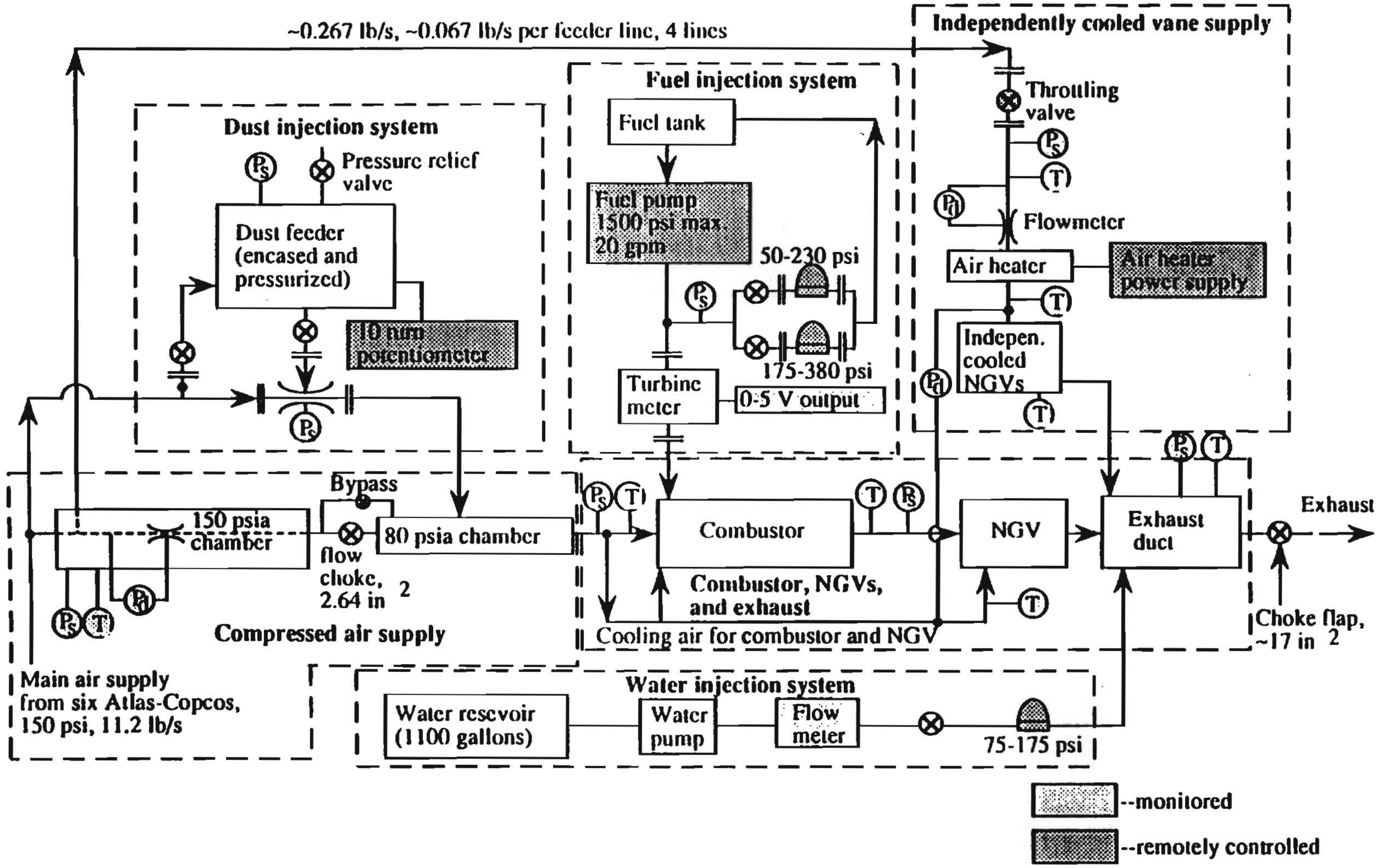


Figure 3. Schematic of F-100 HSTS.

section is controlled by the flow choke area between the high and low pressure chambers. The pressure within the test section is set by adjusting the choke flap area at the exit of the exhaust duct. A dust/air mixture is injected into the inlet of the pipe and allowed to come into equilibrium before entering the combustor. Fuel is supplied to the combustor using a separate fuel delivery system. The combustion products are passed through the high pressure vane which are cooled with approximately 6% of the main air flow. The cooling air ports which would normally be used to route cooling air to the vanes and rotors downstream of the first vane were blocked off in this test configuration. Due to the high temperature of the exhaust gases, water jets downstream of the vanes were used to reduce the exhaust gas temperature down to an acceptable level. A photograph of the test section showing the combustor with the vanes in place along with the water injection nozzles is given in Fig. 4. A general view of the HSTS is shown on Fig. 5.

Provision was made to cool two of the vanes (each vane unit contains two airfoils) independently from the remainder of the vane row to determine the effect of increasing or decreasing cooling air (and thus vane temperature) on material deposition. These vanes are hereafter referred to as ICVs (independently cooled nozzle guide vanes). A schematic of their piping is shown on Fig. 6. A Platnium-Rhodium thermocouple was installed in one of these ICVs at 20% chord on the pressure side so that the operating temperature of this NGV could be continuously recorded.

2.3 DETERMINATION OF DUST FEED RATES.

Because the air ingested by the engine at the inlet is compressed in making its way to the combustor, the dust concentration at the combustor inlet is significantly higher than at the engine inlet. The rate at which dust is fed into the HSTS must reflect this compression ratio. It is necessary to calculate the proper rate at which to feed dust into the HSTS such that the dust concentration at the inlet is equivalent to the dust concentration at the engine

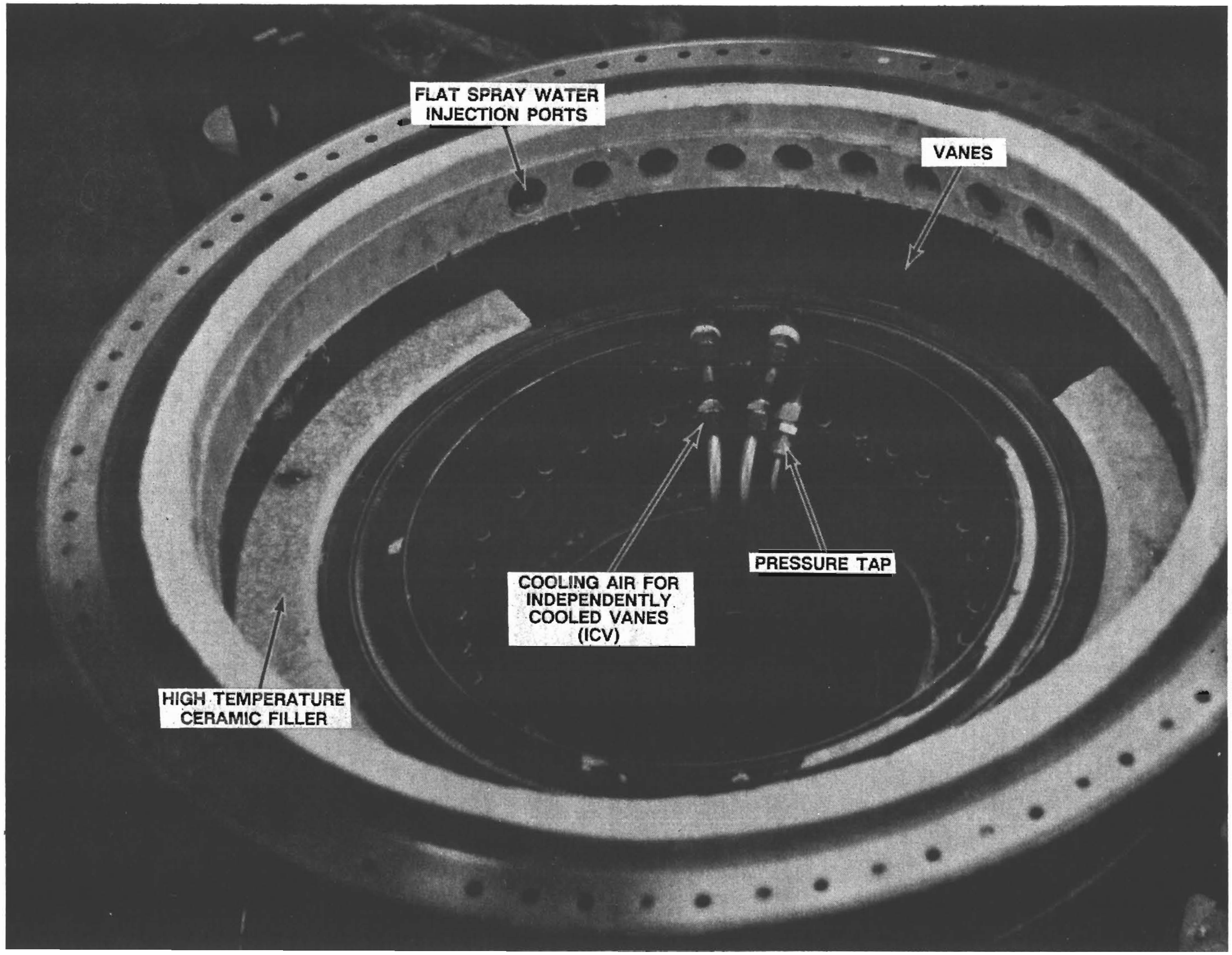


Figure 4. Internal view of F-100 HSTS.

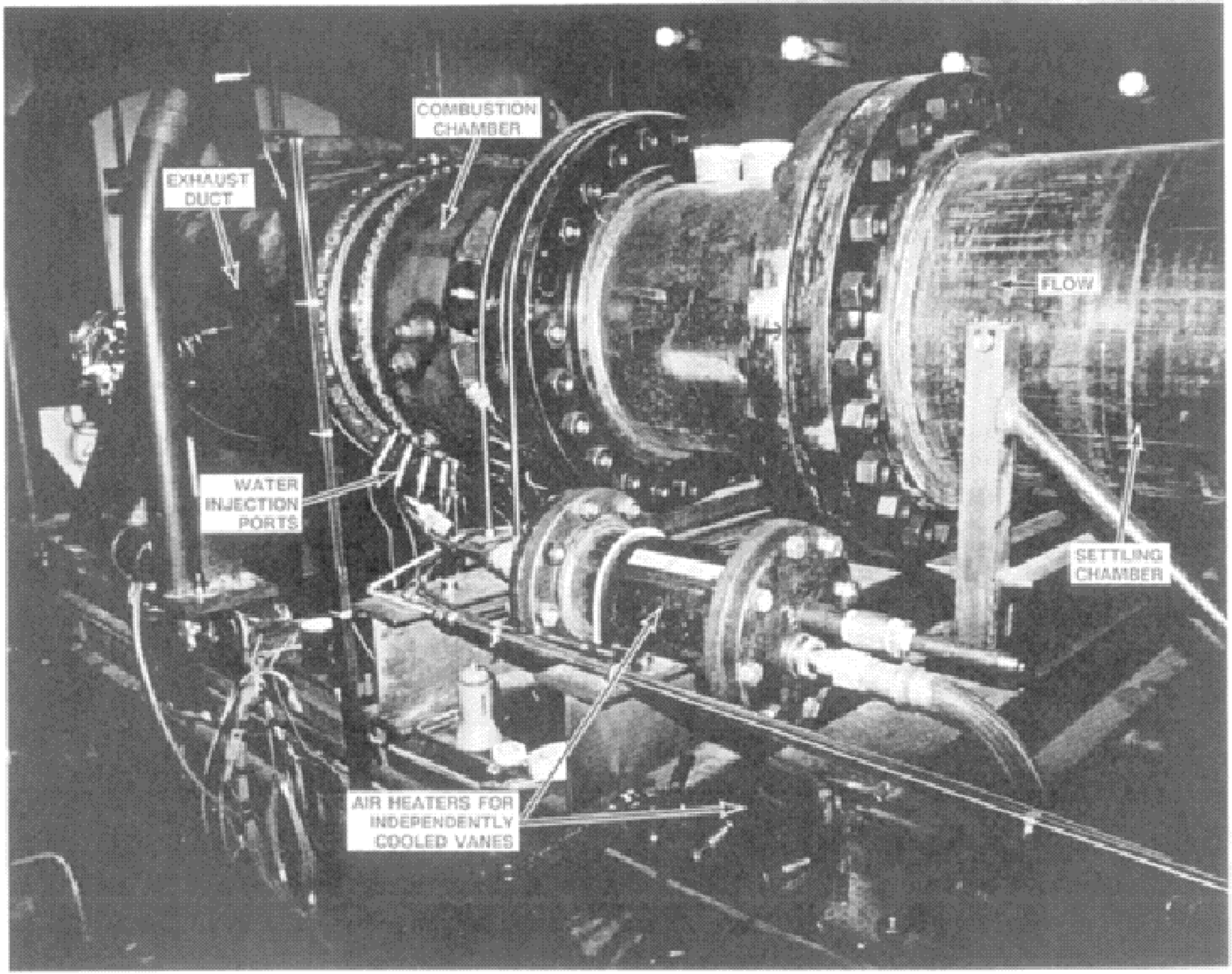


Figure 5. General view of F-100 HSTS.

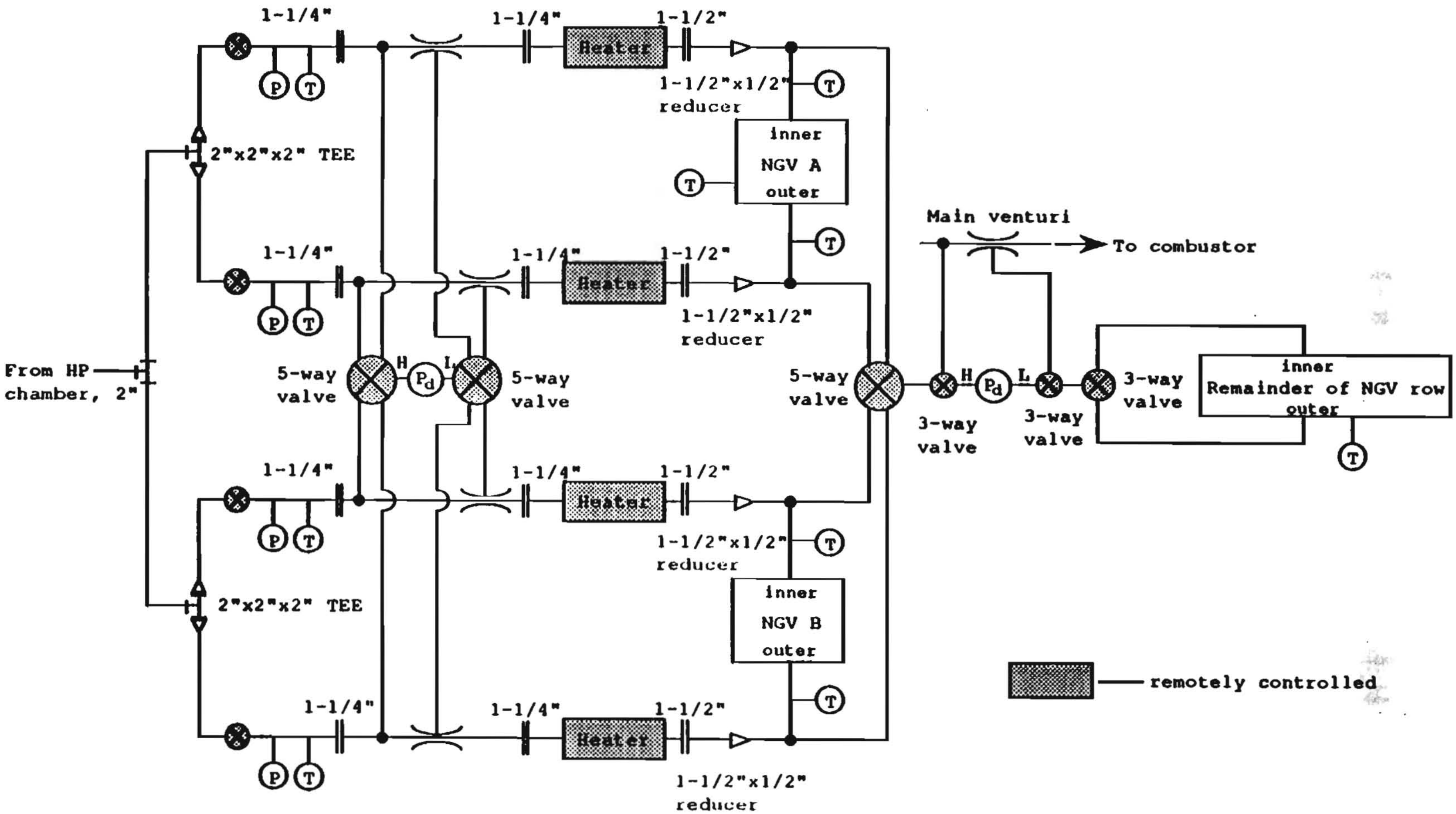


Figure 6. Schematic of vane cooling system.

combustor inlet. It has been shown Dunn and Kim (1991) that the appropriate dust concentration at the HSTS inlet is given by

$$c_{1,\,HSTS} = \frac{M_{engine}}{M_{HSTS}} c_{1,\,engine}$$

where $c_{1,HSTS}$ =dust concentration at the HSTS inlet

$c_{1,engine}$=dust concentration at the engine inlet

M_{engine} =engine magnification factor

$=\rho_{engine\ compressor\ exit}/\rho_{engine\ compressor\ inlet}$

M_{HSTS} =HSTS magnification factor

$=\rho_{HSTS\ compressor\ exit}/\rho_{HSTS\ compressor\ inlet}$

The dust feed rate is then given by

$$F = \dot{V}_{1,\,HSTS}\, c_{1,\,HSTS}\ .$$

For an F-100 engine operating at sea level takeoff, the engine magnification factor can be computed to be M_{engine}=7.82. The HSTS has a magnification factor of M_{HSTS}=4.65 associated with it. For an inlet concentration of $c_{1,engine}$=200 mg/m^3 at the engine face, the corresponding dust concentration at the HSTS inlet is then $c_{1,HSTS}$=(7.82/4.65)*200 mg/m^3=336 g/min. Six Atlas Copco compressors in series can supply a mass flow rate of 255 m^3/min (9000 cfm) of air at the inlet. To achieve a dust concentration of 200 mg/m^3, a dust feed rate of 86 g/min into the combustor is required.

2.4 DATA ACQUISITION.

Data acquisition was performed using an IBM AT compatible along with a Kiethley 500 intelligent acquisition system. All pressures, temperatures and flow rates were acquired every five to ten seconds and stored in data files. Time records of all the important variables throughout the experimental facility were thus obtained. A sample of the data is shown on Fig. 7 a,b.

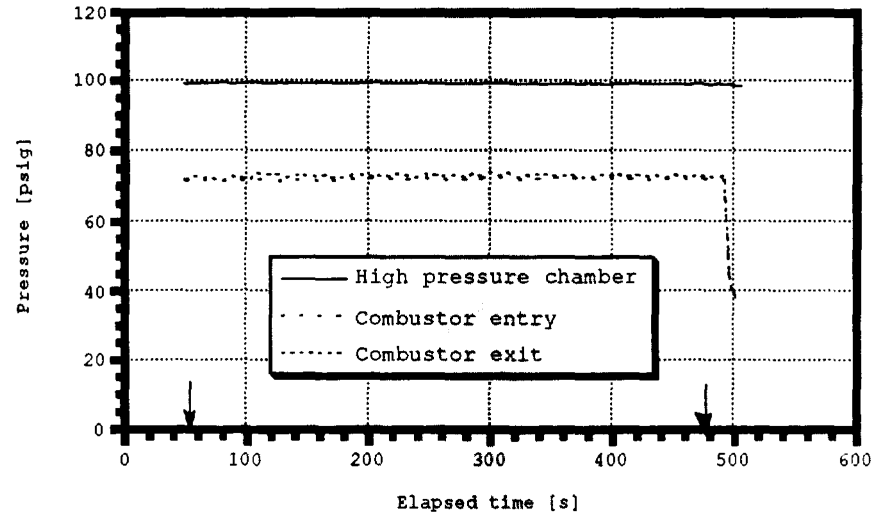


Figure 7a. Pressure vs time traces for run 8.

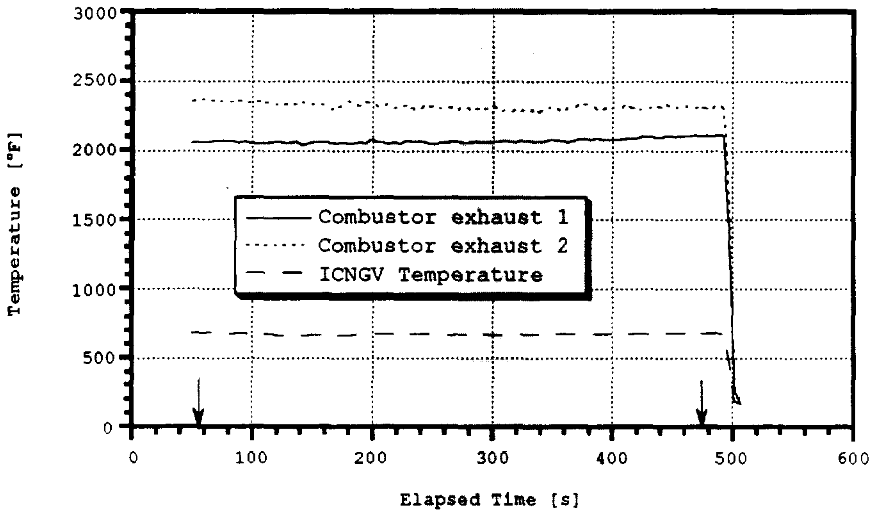


Figure 7b. Temperature vs. time traces for run 8.

SECTION 3

DISCUSSION OF RESULTS

A summary of the 18 runs completed during the course of this study is shown in Table 2. The test duration for each run was 7 minutes, and all except the first two runs were at a targeted TIT of 1644 K (2500 °F). Dust concentrations varied from 200 mg/m^3 (the baseline concentration) to 1000 mg/m^3. A brief narrative of the results from each run is given following Table 2.

Table 2. Summary of test runs.

Run	Blend	TIT (K)	Engine face dust conc. (mg/m^3)	Comments
1	7	1422	200	No deposits on TITs or vanes .
2	7	1533	200	No deposits on TITs or vanes .
3	7	1644	200	No deposits on TITs or vanes .
4	8	1644	200	Glass covered TITs, clean vanes .
5	9	1644	200	Aborted run.
6	9	1644	200	Actual TIT of 1616 K (2450 °F). Some glass on TITs, clean vanes. Some burned vane leading edges. Clogged dust feeder.
7	9	1644	200	Actual TIT of 1561 K (2350 °F). Little glass on TITs, clean vanes.
8	5	1644	200	Actual TIT of 1533 K (2300 °F). No deposits on TITs or vanes.
9	10	1644	200	No deposits on TIT or vanes.
10	2	1644	200	Glass on TITs, no deposits on vanes.
11	2	1450	200	Glass on TITs, no deposits on vanes.
12	2	1644	500	Glass on TITs, little deposits on vanes.
13	2	1644	1000	Glass on TITs, little deposits on vanes.
14	2	1644	500	With decreased airflow to ICV. Glass on TITs, significant deposits found on ICV pair.
15	7	1644	500	Glass on TITs, no deposits on vanes. Damage to ICV from 10-25% chord on suction side.
16	Dried blend 2	1644	500	Glass on TITs, no deposits on ICVs probably due to damage to ICV pair.
17	2	1644	500	Glass on TITs, no deposits on ICVs probably due to damage to ICV pair.
18	MSH	1644	500	Glass on TITs, no deposits on ICVs, probably due to damage to ICV pair.

The ICVs were operated with more cooling air than their neighbors during runs 1-13 to investigate the effect of cooler vane metal temperatures on deposition behavior.

Run 1: TIT=1422 K (2100 °F), 7 minute dust duration, Blend 7, 200 mg/m^3. A drop in TIT of ~56 K (100 °F) within ~1 minute was observed when the dust was turned on. No deposits were expected during this run as no deposits were seen in the T56 HSTS which operated at a TIT of 1450 K (2150 °F). Borescope: No deposits were found on either the TIT probes or on the vanes.

Run 2: TIT=1533 K (2300 °F), 7 dust duration, Blend 7, 200 mg/m^3. Borescope: No deposits were found on either the TIT probes or on the vanes (see comments below).

Run 3: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 7, 200 mg/m^3. TIT dropped ~56 K (100 °F) initially, then increased to ~1700 K (2600 °F) at 6 minutes after dust initiation. Borescope: No deposits were found on either the TIT probes or on the vanes (see comments below). It was thought (rather prematurely as discussed in the following discussion) at this point that no deposits would be observed in the engine combustor for the "most probable" blend (blend 7).

Run 4: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 8, 200 mg/m^3. Borescope: No deposits were seen on either the TIT probes or on the vanes (see comments below).

After run 4, the TIT probes were removed to move them to different positions. They were found to be covered with a clear glass on the front side and a mixture of glass and soot on the back side. A photograph of a TIT probe covered with this clear glass is shown on Fig. 8. The clear glass on the front of the probes was not obvious through the

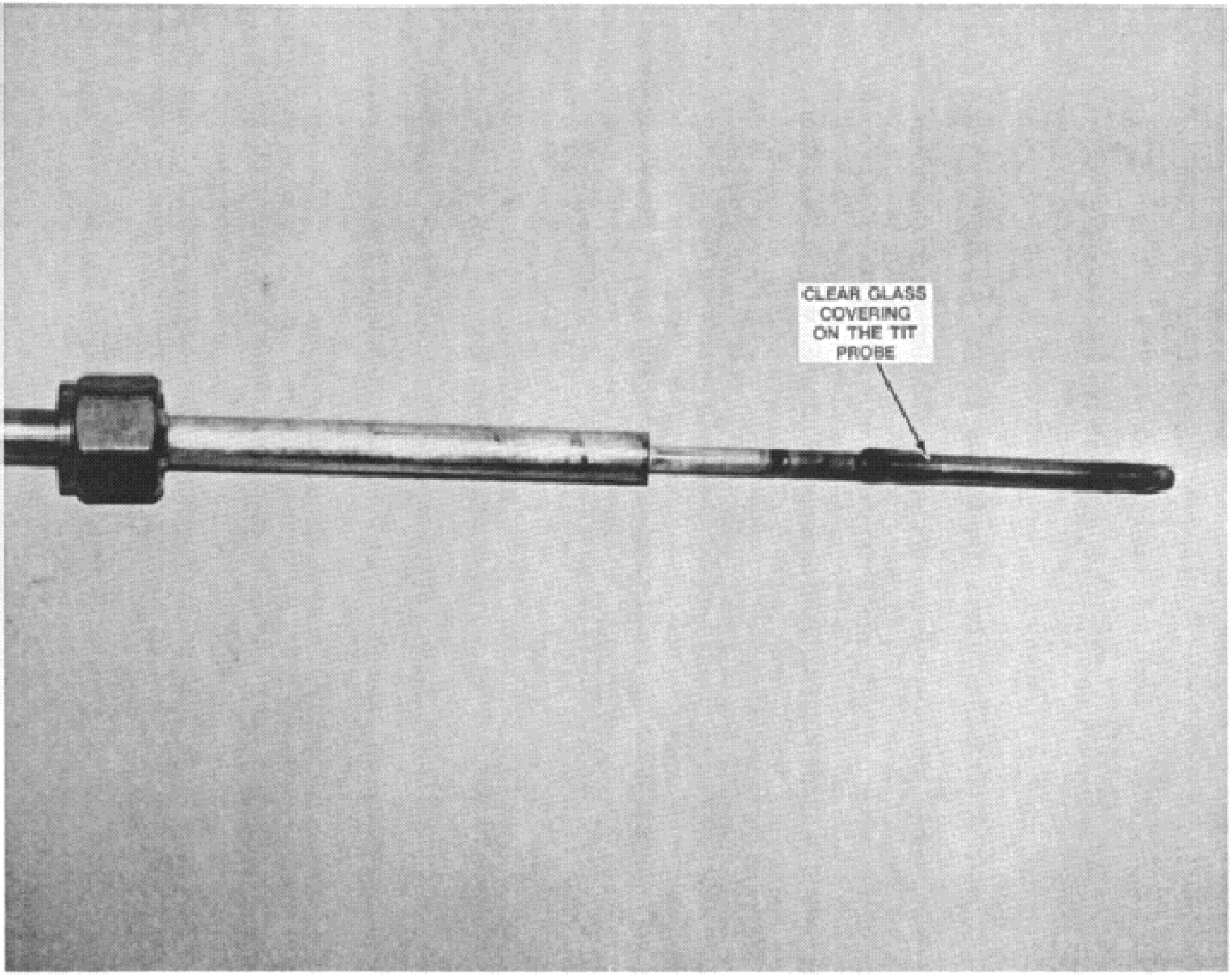


Figure 8. Glass covered TIT probe.

borescope, and thus the TIT probes were thought to be clean after runs 1-4. The back end of the combustor was then pulled off to check if the vanes were also covered with this glass. However, no deposits were seen on the vanes. Samples of the glass deposits on the TIT probes were collected. The glass was very difficult to remove from the TIT probes, requiring a hammer to break it free. It was felt at this point that glass deposition occurs on the TIT probes but not on the vanes probably because the surface temperature of the TIT probes in the HSTS was much hotter than the vane suraface temperature. Even in the engine, the vane metal temperature would be less than the temperature of the TIT probe, but not as much less as for the currently configured HSTS. Surface temperature was thus suspected to be an important parameter in determining whether or not deposition would occur.

Run 5: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 9, 200 mg/m^3. An aborted run. Difficulty was encountered in getting ignition in the combustor. The four fuel nozzles were pulled from the combustor and inspected. The back side of the fuel nozzles was found to be caked with dust, which may have prevented the swirl and recirculating flow within the combustor which is necessary for proper combustor operation. This problem was felt to be due to moisture in the incoming air stream. Also, the fuel nozzle directly upstream of the ignitor was found to be clogged. All the fuel nozzles were cleaned and the clogged fuel nozzle replaced. From this point on, the fuel nozzles were cleaned and inspected after every run. It should be noted that during the full-scale engine tests (Dunn, M.G. 1990a,b) the front side of the fuel nozzles became coated with a black carbon-like material that prevented atomization of air and relight. The nature of the fuel nozzle deposition experienced in the HSTS was not, however, the same as experienced in the engine.

Run 6: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 9, 200 mg/m^3. A repeat of the conditions in Run 5. A TIT of 1561 K (2350 °F) to 1617 K (2450 °F) was reached, which was lower than the target TIT. Borescope: Some glass was found on the TIT, but not nearly as much as after Run 4. No deposits were found on the vanes. The leading edges of some of the vanes were found to have burned away (<10% chord, 70%-100% span). As the damage to the vanes was not extensive, a decision was made to run with the vanes in the damaged condition as long as possible. It was also found that the dust feeder had clogged during the run. The run was therefore repeated.

Run 7: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 9, 200 mg/m^3. A repeat of run 6. A TIT of 1561 K (2350 °F) was achieved, which was lower than the target TIT. Borescope: Very little deposits were found on the TIT probes. No deposits were found on the vanes. No further damage to the vanes was observed. A surface temperature of >1589 K (2400 °F) seems necessary in order for glass to deposit on the TIT probes.

Run 8: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 5, 200 mg/m^3. A TIT of 1550 K (2330 °F) was achieved. Borescope: No deposits were found on either the TIT probes or the vanes. This supports the earlier speculation that a surface temperature greater than 1589 K (2400 °F) appears to be necessary for glass to deposit on the TIT probes.

Run 9: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 10, 200 mg/m^3. As this blend contains no glass, no deposition of material on either the TIT probes or the vanes was expected. A TIT of 1644 K (2500 °F) was achieved. Borescope: The TIT probes were found to be covered with glass. The glass was clear on the front, as observed earlier. The vanes had a reddish discoloration on the first 50% of the chord. Since there was the possibility of glass underneath the dust, the HSTS was taken apart to get a better look at the vanes. The reddish discoloration seen during borescoping turned out to be dust on the vane surface. This dust was easily scraped off. No glass was found on the vane surfaces. The fact that glass was found on the TIT probes for a run where no synthetic glass was present in the dust blend suggests that some other component(s) in the blend is responsible for the deposition on the TIT probes.

The results to this point all indicated that the dust blends containing the synthetic glass do not deposit unless the surface onto which the particles impact is at a temperature greater than ~1589 K (2400 °F). It was decided to proceed to blend 2, the scoria containing blend.

Run 10: TIT=1644 K (2500 °F), 7 minute dust duration, blend 2, 200 mg/m^3. A sharp rise in TIT was observed soon after the dust was turned on. Fuel flow was cut back from a nominal value of 8.59 l/min (2.27 gpm) to 7.31 l/min (1.93 gpm) to maintain indicated TIT at 1644 K (2500 °F). It is speculated that molten particles from the hot zone of the combustor impinge on the TIT probes and deposit, giving up their heat in the process. This causes the indicated TIT to increase above the actual gas flow temperature. Borescope: The TIT probes were found to be covered with glass. However, the vanes had a reddish dust covering them, but no significant deposits were found.

The fact that blend 2 did not deposit on the vanes was an interesting result, especially since blend 2 was observed to cause deposition when run in the engine. The focus of the study now changed to determine what mechanism(s) controls the deposition behavior of blend 2. Three points of difference between the HSTS and the engine combustor were thought to be significant. Specific tests were developed to test each hypothesis. First, the previous engine tests were run at conditions for which the TIT did not reached the levels obtained in the HSTS. It was speculated that perhaps the TIT needed to be <u>lowered</u> to get blend 2 to deposit. A run at a TIT of 1450 K (2150 °F) was selected since blend 2 deposited in the previous T56 HSTS at this TIT. Second, the concentration of blend 2 used in the engine tests and the T56 HSTS tests were 500 mg/m^3 and 1000 mg/m^3, respectively.

A test was made with the increased concentrations to determine whether or not deposition occurs. Third, the temperature of the cooling air coming into the vanes in the engine is much higher (~756 K) than in the HSTS (~328 K). This means that the vane surface tempertaure is much hotter in the engine than in the HSTS. A test was made with reduced cooling air to the independently cooled vane pair to determine the effect of vane surface temperature on deposition.

Run 11: TIT=1450 K (2150 °F), 7 minute dust duration, blend 2, 200 mg/m^3. This was a test of the first hypothesis. The TIT was maintained at 1450 K (2150 °F) (±5.6 K) during the test. Borescope: Glass covered TIT probes were found as in the previous run. This is in contrast to the synthetic glass containing blends (the "most probable" blends) which required a surface temperature of greater than 1589 K (2400 °F) in order for deposition of occur. The vanes were clean, suggesting that decreasing the TIT does not cause deposition of blend 2 to occur. The results of this test, however, verified that blend 2 deposits on surfaces which are at temperatures much lower than those required to get the synthetic glass containing mixtures to deposit. The reader is reminded that surface temperatures in excess of 1589 K (2400 °F) were required in order to get the "most probable" synthetic glass containing blends (blends 7-10) to deposit.

Run 12: TIT=1644 K (2500 °F), 7 minute dust duration, blend 2, 500 mg/m^3. Test of second hypothesis. The TIT was steady at 1644 K (2500 °F) throughout the run. Borescope: TIT probes were covered with glass. Some deposits were found on the vanes, but not nearly as much as in the engine or the T56 HSTS runs. The HSTS was taken apart and the deposits were collected.

Run 13: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 2, 1000 mg/m^3. Test of second hypothesis, but at a higher concentration. TIT increased to 1708 K (2615 °F) during run. Borescope: The TIT probes were covered with clear glass. The vanes have caked dust on the leading edges and further back, but not nearly as much as in the engine or the T56 HSTS. The HSTS was taken apart and the deposits were collected. Some clogging of the vane cooling air inlets (see Fig. 9), which has the effect of decreasing the cooling air to the vanes, was also noticed. The results of the above two tests indicated that concentration does not play a significant role in determining whether or not a dust blend deposits. The concentration is important once deposition begins to occur.

It was interesting to note that deposits usually occurred at locations where the vane had been damaged (the local vane temperature at these points was sufficiently high to cause melting of the vane surface). A photograph of the vane row before and after the deposits were removed (Fig. 10 a,b) illustrates this point. This behavior again suggests that the surface temperature onto which the particles impact must be above a certain threshold temperature if deposition is to occur. Furthermore, a comparison of the blend 9 and the blend 2 results suggests that deposition is also dependent upon the physical characteristics of the impinging material.

Inspection of the above photographs reveals another damage mechanism (one separate from deposition) that can occur in engines. Close inspection of the leading edges of the vanes shows that the showerhead cooling air holes have been plugged with dust, resulting in a decrease in film cooling effectiveness. This plugging allows the surface temperature of the vane to increase above the vane melting temperature, resulting in damage to the vanes. Shown on Fig. 11 is a closeup view of the leading edges of two vanes that shows regions where clogging of the cooling holes has occurred and the resultant damage to the vane. It is suspected that this mechanism caused the damage to the leading edges of the vanes that was observed during post-test inspection after run 6.

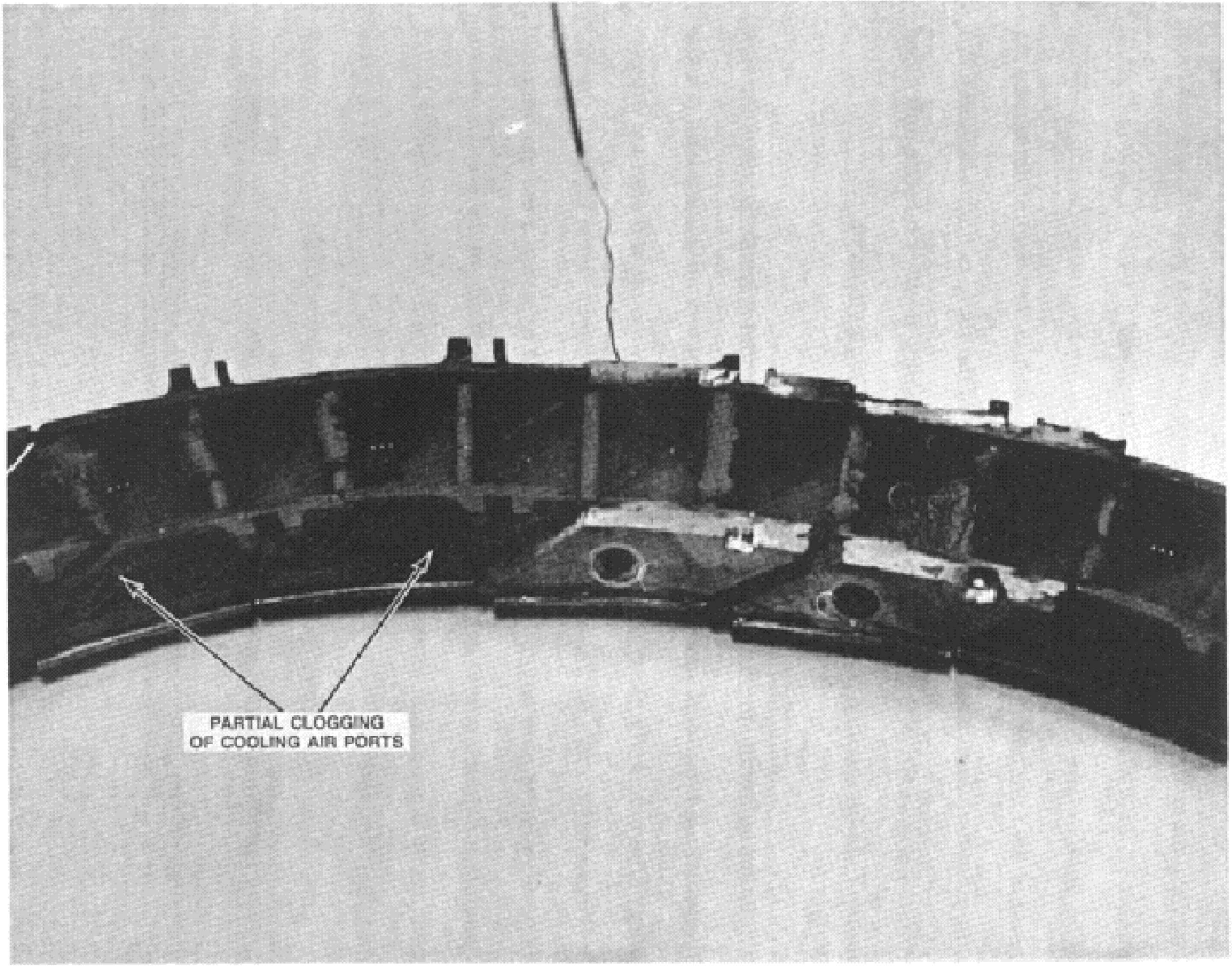


Figure 9. View of nozzle guide vanes showing partial blockage of cooling air ports.

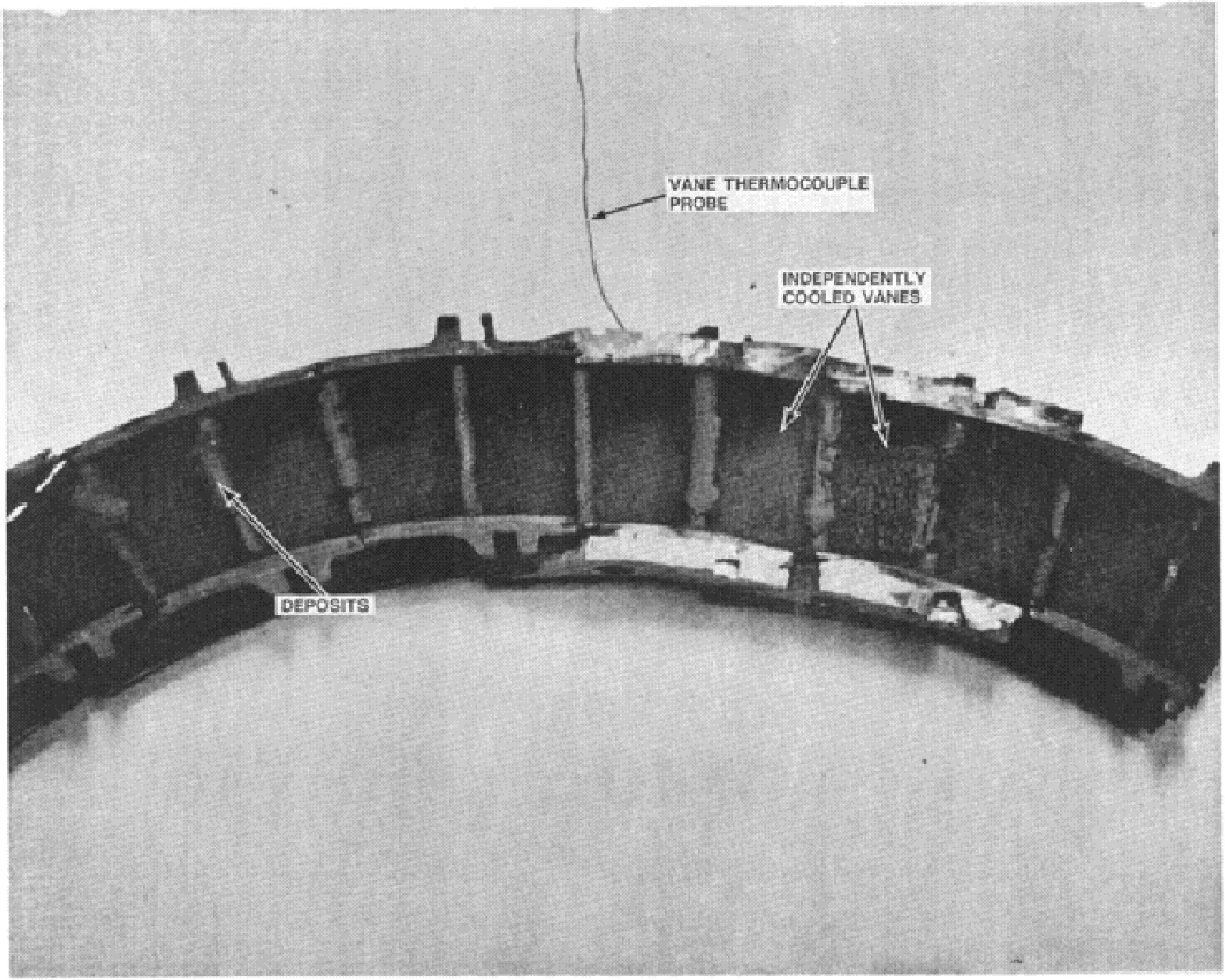


Figure 10a. Deposits on vane row (after run 11).

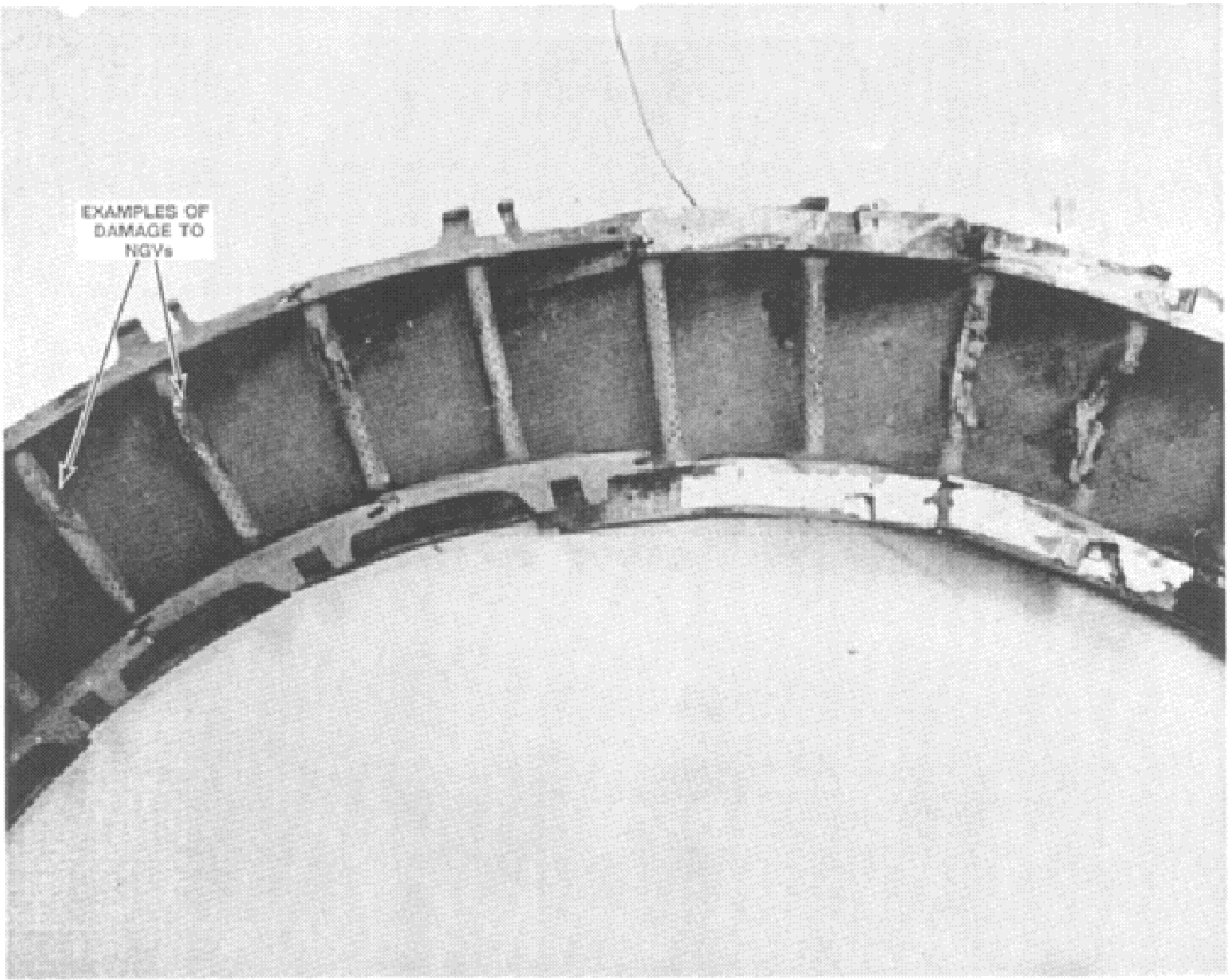


Figure 10b. Vane row after removal of deposits (after run 11).

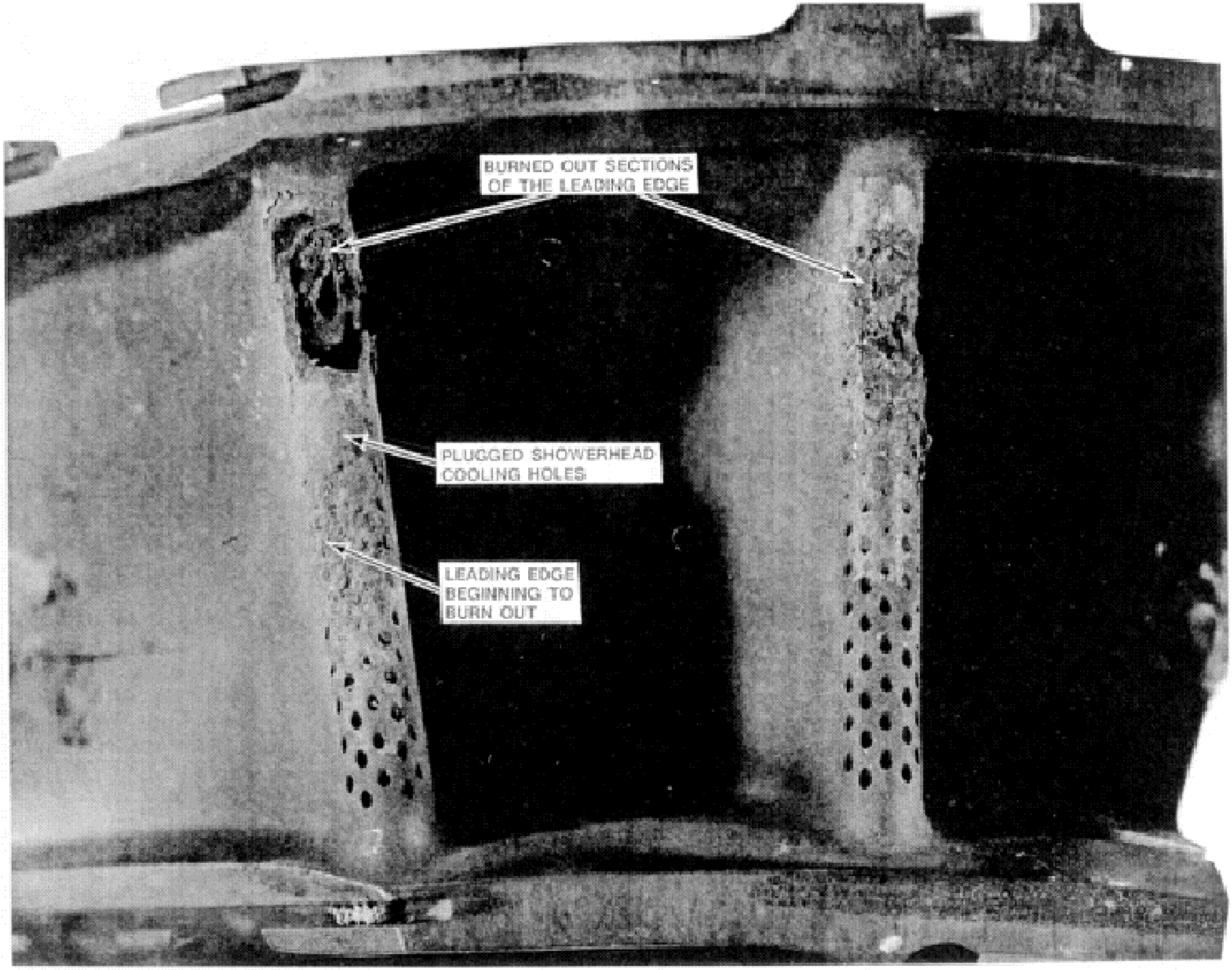


Figure 11. Closeup view of vane leading edge showing clogging of the cooling holes and the resultant damage.

Run 14: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 2, 500 mg/m^3. This was a test of the third hypothesis. The temperature of the ICV (which consistently had been held at ~644 K (700°F) throughout all the previous runs) was increased by decreasing the cooling air to it. Although an ICV temperature of 783 K (950 °F) was targeted, the temperature reached a maximum of ~1089 K (1500 °F) during the run. TIT was steady at 1644 K (2500 °F) throughout the run. Borescope: Significant deposits were found on the ICV. Smaller amounts of deposits were found on the other vanes as indicated in Table 3. The TIT probes were covered with glass. The HSTS was taken apart and the deposits were collected. Increasing the vane surface temperature significantly increased the amount of deposition. This parameter seems to be the key to determining whether or not a particular dust blend deposits. It was decided to verify whether or not one of the mixtures containing synthetic glass would deposit on the ICV at elevated temperature. Run 15 is a repeat of run 14 with blend 7 replacing blend 2.

Table 3. Deposit distribution on vanes after run 14.

Location	Mass of dust collected (g)
From ICV	15.96
From vane next to ICV	5.50
From remainder of vanes	6.98

Run 15: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 7, 500 mg/m^3. TIT was steady at 1644 K (2500 °F) throughout the run. The ICV temperature increased to 1106 K (1530 °F), then dropped to 672 K (750 °F), then increased and leveled off at ~811 K (1000 °F). Borescope: Very little deposits were found on the ICV. The TIT probes were covered with glass. The back end of the vane next to the ICV where deposits were found (5.5 g) on the previous run was burned away. A photograph of this vane is shown on Fig. 12. It was found later (after Run 18) that the cooling air ports for this burned vane were blocked off by caked dust, preventing passage of cooling air flow. The temperature

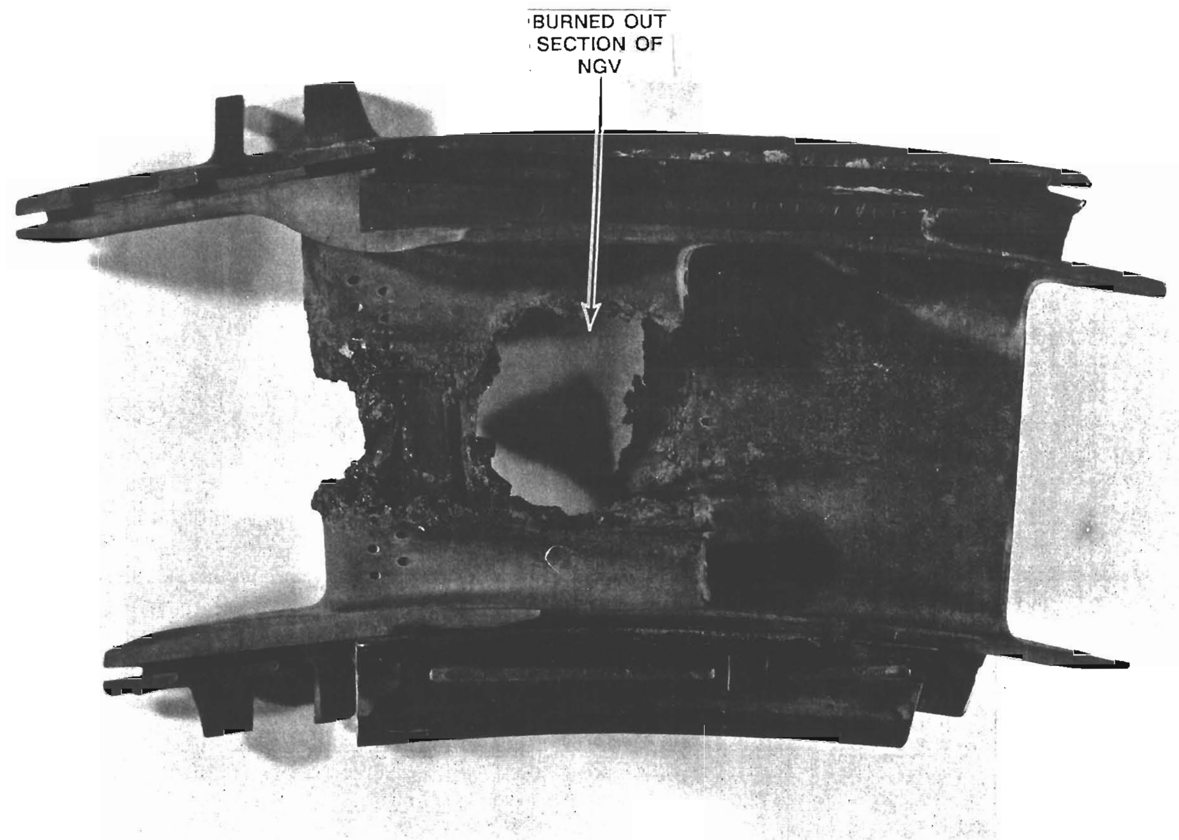


Figure 12. Photograph of burned out vane after run 15.

of the vane increased sufficiently to cause the back end of the vane to melt. It is suspected that this process began during run 14, which allowed the vane surface temperature to increase sufficiently to enable blend 2 to deposit during that run. The suction sides of the ICV had also burned away from ~10% to 25% chord, indicating ICV temperatures reached the melting point of the vane material. The fact that deposition was not seen on the ICV suggests that deposition of the synthetic glass occurs only at temperatures above the vane metal melting point. Since the vanes run at temperatures lower than their melting point in an engine, it is felt at this time that deposition will probably not occur in the engine when using the "most probable" blend. The above is supported by the observation that deposition of the "most probable" blend only occurs on the TIT probes for probe temperatures above ~1589 K (2400 °F), far above the vane material melting temperature.

To repair and re-instrument the ICVs was going to require more time than was available. Therefore, a decision was made to continue running the HSTS in its present condition and obtain whatever relevant data possible. Blend 2 containing the dried scoria was run next. If the hypothesis that driving off the bound water makes the scoria more "pure" by reducing the impurities (of which water is one of the most pervasive) is correct, then this blend should exhibit less of a tendency to deposit.

Run 16: TIT=1644 K (2500 °F), 7 minute dust duration, Dried Blend 2, 500 mg/m^3. The TIT probes were not reading correctly due to damage sustained during testing to this point in the test matrix, so this run was therefore performed using fuel flow as an indicator of TIT. The fuel flow required to obtain TIT=1644 K (2500 °F) was found from previous runs to be consistently near 2.27 gpm. The fuel flow throughout this run was held at this flow rate. The indicated ICV temperature varied from 594 K (610 °F) to 811 K (1000 °F). This variation was felt to be due to the damage done to the ICV during run 15. Borescope: The TIT probes were coated with glass. No deposits were observed on the vanes, which was unexpected and warrented further verification checks to ensure the operational state of the HSTS.

It was clear at this point that the ICVs had been badly damaged, so it was decided to re-run Blend 2 with the un-dried scoria to determine if this damage to the ICV had caused unreliable results for the dried Blend 2 (Run 16).

Run 17: TIT=1644 K (2500 °F), 7 minute dust duration, Blend 2, 500 mg/m^3. Borescope: The TIT probes were covered with glass. No deposits were seen on the ICV. This test confirmed the suspicion that the HSTS was not giving reliable results due to the severe damage to the ICV. It was, therefore, not possible to answer the question as to whether or not the dried blend 2 would have deposited. However, one final run using a different material that has often been used in these combustors was made to confirm that the HSTS was not operating properly.

Run 18: TIT=1644 K (2500 °F), 7 minute dust duration, MSH, 500 mg/m^3. A run was made with MSH to check if deposition of MSH would occur. Borescope: The TIT probes were found to be covered with glass. No deposits were seen on the ICV. This set of results along with run 17 were sufficiently convincing that testing was terminated pending repair of the HSTS.

SECTION 4

CONCLUSIONS

A test facility was designed and constructed using F-100 engine hardware to enable one to determine the behavior of various dust cloud materials when they are ingested into a gas turbine combustor flow. The test series reported here was designed to test the behavior of several blends constructed using the "most probable" constituents of the dust cloud. These constituents were Ottawa quartz, red art clay, feldspar, peat moss, and a synthetic glass made from these constituents. No significant deposition of the blends containing the synthetic glass was observed to occur on the turbine vanes. The most significant parameter that determines whether or not a particular material deposits was found to be the temperature of the surface onto which the molten particles impact. The test results indicate that "most probable" blends will deposit on surfaces with temperatures greater than ~1589 K (2400 °F). Similar results were found for the scoria containing blend, but with the metal surface threshold temperature for deposition closer to ~1089 K (1500 °F).

This test series also revealed several potential engine hot section damage mechanisms. First, dust may clog the vane showerhead cooling ports, causing loss of cooling air to the leading edge region. If the engine is operated in this mode at a sufficiently high thrust setting, this lack of cooling air can cause the vane to start burning out at the leading edge. The remainder of the vane can also progressively burn out. This damage mechanism can occur on any of the vanes. Second, dust laden air that is used to cool the vanes can carry dust into the vane cooling air inlet ports, which can result in clogging. The inner cooling air ports (the ports entering the vane from the vane hub) supply air to the showerhead film cooling holes. The outer cooling ports (the ports entering the vane from the vane tip) supply cooling air to the suction side film cooling holes in addition to providing internal cooling of the rear of the vane before exiting through slots in the vane trailing edge. If the inner cooling ports become clogged, the vanes can burn out at the leading edge. Clogging of the outer cooling air ports can result in the back end of the vanes burning out. This damage mechanism seems to affect the vanes that are lower in elevation, since gravity causes dust to settle to the bottom of the test section. Both of the engine damage mechanisms discussed above can occur even if the ingested material does not deposit on the vanes. The third damage mechanism is deposition of material on the vanes, which reduces the flow area of the first vane row. The results presented in this report demonstrate that deposition of material on the turbine vanes is very dependent upon the characteristics of the dust cloud constituents and upon the vane metal temperature.

SECTION 5

LIST OF REFERENCES

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APPENDIX

NOMENCLATURE

A	Area
c	Specific heat or concentration, depending on context
d	Diameter
F	Dust feed rate
FF	Flow function
h	Heat transfer coefficient
ICV	Independently cooled nozzle guide vane
k	Thermal conductivity
M	Dust magnification factor
m	Mass
MSH	Mt. St. Helens ash
Nu	Nusselt number
P	Pressure
R	Gas constant
T	Temperature
TIT	Turbine inlet temperature
$\dot{V}$	Volume flow rate
v	Velocity
$\dot{w}$	Mass flow rate
μ	Dynamic viscosity
ρ	Density
τ	Time constant

Subscripts

f	Fluid
p	Particle
t	Thermal
∞	Freestream

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